DEVELOPMENT OF OPTIMALLY TUNED STATCOM CONTROLLERS FOR IMPROVED REACTIVE POWER COMPENSATION IN POWER SYSTEM

A SYNOPSIS

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1. Introduction

Electric power is essential for modern life, and the demand for it is increasing daily due to various factors such as domestic use, industrial development, transportation, and agricultural activities. Two critical aspects of any power supply system are its reliability and quality. A sustainable power distribution system must provide uninterrupted electricity 24 hours a day, 365 days a year. Power Quality(PQ) is defined at customer connection points as maintaining a near-sinusoidal voltage at a frequency of 50 or 60 Hz. The transmission and distribution of electrical power face heavy traffic due to increased demand and the integration of renewable energy sources like solar and wind into the grid. These sources require power electronic converters to regulate power flow, ensuring that modern converters inject or absorb real and reactive power to maintain the health of the power system. Key power quality parameters include voltage sag and swell, power factor, and harmonics. These parameters must stay within specified limits to ensure efficient system operation.

All electrical devices are prone to failure or malfunction when exposed to one or more PQ problems. All the electrical devices which are connected to the system is called as loads. It may be a motor, generator, transformer, computers, modern gadgets, communication devices and house hold appliances. Depending on the severity, all of these devices react negatively to PQ concerns. In electronics world, majority of the equipment's/appliances are inductive in nature. Inductive loads affect system performance by consuming reactive power from sources due to phase difference between voltage and current which one makes poor power factor in power system.

To meet these increased inductive loads, power system components need to carry additional reactive power along with real power supplied from source. It will make additional burden to the transmission network and components and leads to energy losses. Apart from reactive power, electronic appliances make harmonics in power system. So, utilities would like to strengthen the transmission system by building more interconnectors. It is rather difficult to obtain permission from the local authorities for new routes of transmission lines such as building new transmission lines, permission from former for agriculture land and environmental considerations.

High-speed power electronic devices provide effective solutions to power quality issues by employing advanced compensation techniques. Among these devices, Flexible AC Transmission Systems (FACTS) are instrumental in maintaining smooth

power system operation while ensuring power quality. Of the FACTS devices, the STATCOM (Static Synchronous Compensator) is the most effective, thanks to its fast dynamic response to load changes. It improves system performance and ensures stable power transmission without disturbances. STATCOM is connected through an interface filter and parallel to the load at the Point of Common Coupling (PCC).

This research work applies novel tuning methodologies and advanced control strategies to STATCOM for enhancing the performance parameters of the power system such as reactive power compensation, power factor, Total Harmonic Detection (THD) value and voltage fluctuations under nonlinear, unbalanced and inductive loads as well as various fault conditions.

2. Literature Survey

The definition of "good" and "bad" power is according to the individual who will be using it. When equipment/appliance performs up to the user's expectations, they will have a positive impression of the power. When the equipment/appliance does not perform as expected or gives out before its time, people tend to assume that there is something wrong with the power. The bad power occurred by not maintaining PQ parameters within limits. Understanding power quality issues is a good starting point for solving any power quality problem.

Gyugyi & Laszlo suggested AC distribution system, power quality issues emerge from nonlinear loads and unexpected additional load on the distribution network [1]. Multiple factors determine the quality of power delivered to the consumer. They exhibit a constant voltage magnitude, balanced phases, a consistent frequency, absence of harmonic content, no interruptions, an appropriate power factor, and the capacity to withstand faults and recover swiftly. The authors Norouzi & Sharaf, suggesting the utilities should focus on disruptions originating from end-user equipment as the primary potential quality concerns [2].

Authors Dixon et al FACTS devices equipped with the controller facilitate voltage management, reactive power compensation, power factor correction, and the elimination of current harmonics [3].

Authors Rao et al, are suggesting the L filter is primarily employed in the VSC topology as a result of its inherent simplicity [4]. A large value of inductance L is necessary to achieve a sufficient level of ripple attenuation. It results in a high voltage

drop, power loss, high cost, and a reduced slew rate, which in turn affects the dynamic performance of the system.

The author of the article Bollen proposed various filters are used to attenuate the harmonics [5]. But the L filter and LC filters are having more resonance which influences the system's stability.

The authors of the research article Tang et al suggesting LCL filter generates output currents with a high slew rate, facilitating precise harmonic compensation while avoiding unnecessary overmodulation during transients [6]. Stability considerations are more complex but can be addressed using the proposed design and control tuning methods.

The authors Reznik et al proposed the experimental evaluation of the methodology has demonstrated its effectiveness in ensuring adequate damping, overall stability, and a seamless transient response, facilitated by a more thorough and generalized design process [7].

Authors Lee J et al implemented PI controller for regulate the real and reactive components of STATCOM current [8]. Another authors Firas Marwan Fakhreddin et al suggesting PI controllers are developed via trial-and-error process, including efficiency and performance exchanges [9]. However, these controllers are limited in their capacity to provide effective control and transient stability improvement across a broad variety of power system operating circumstances, which is a significant drawback

The authors of the research article Yazdani et al described performing trial-and error research on transmission topology changes is not possible for utility engineers, and the issue could be made worst while transmission topology changes are caused by a scenario [10]. Hence, a nonlinear controller is required in order to improve the performance of nonlinear power system while running under dynamic operating circumstances such as Unbalanced load, Nonlinear loads and faults conditions.

The authors of the research article Xu & Li claimed PI controller operating point is sensitive to controller gain and has a sluggish response to sudden change as well as peak overshoot [11]. So, the closed-loop robustness of the STATCOM is affected. In order to enhance the robustness of the closed loop, Sliding Mode Controllers (SMC) has been developed as a contemporary control method for a wide range of systems, including nonlinear, time-varying, and fault-tolerant systems.

The authors of the research article Mosaad et al claimed SMC have possesses unique characteristics, including robustness and a lack of sensitivity to system

parameter variation [12]. However, the SMC is restricted in that the control action is limited to the sliding surface. Therefore, it is crucial to establish the parameters of the sliding surface. Sliding surface parameters are user-defined values. The higher and lower values of SMC parameters make the controller output to depart from the sliding surface and affect the closed-loop robustness. So, it is necessary to optimize the parameters of SMC to get the stability of the system.

PSO is a meta-heuristic search method proposed by the authors Poli et al based-on population. Each particle represents a swarm and behaves with the cognitive or the swarm's social intelligence. i.e., if one of the particles finds a good path for the food then all the other particles are also able to follow the path irrespective of the distance between the particles [13]. PSO has the advantages over EA based algorithms as it has stable, robust and faster convergence features.

The literature that is now available has shown that while linear controllers, such the PI controller, are used in power quality enhancement studies, they are not appropriate for fault circumstances and dynamic load variations. For nonlinear systems, sliding mode controllers might be appropriate, however they have a significant chattering issue on the sliding surface It is typically difficult to reach a steady state value for SMC during abnormalities using traditional tuning approaches.

3. Objectives

The main objectives of the research are as follows:

i. Development of hybrid Sliding Mode Controllers (SMC) based PI controller for STATCOM to enhance power quality with various loads.
ii. Apply a meta-heuristic algorithm to tune Hybrid SMC parameters to get optimal solution for various load conditions.
iii. Apply the meta-heuristic algorithm to tune the STATCOM parameters under various Fault conditions.

4. Research Problem

The research concentrates on the design and development of hybrid sliding mode controllers for STATCOM and employs a meta-heuristic algorithm to derive optimal values for Kp and Ki for dynamic variation of loads and faults, thereby fine-tuning the hybrid SMC parameters to improve power quality.

In the first work, Hybrid Sliding Mode Controllers based STATCOM has been presented under inductive, unbalanced and Nonlinear loads. The sliding mode

controller is most widely used because of its stable, fast and robust characteristics. It is able to handle disturbances and uncertainties. For our proposed work the sliding surface is designed with proportional plus integral actions with e(t). The proposed controller output has a continuous part and the discrete part. Kp and Ki are the two adjustable parameters that are included in the hybrid SMC. These parameters are used to maintain the controller output at the sliding surface in order to eliminate errors. So, the overall system power quality was enhanced in [14].

The second work is to apply a meta-heuristic algorithm especially Particle Swarm Optimization (PSO) is used to tune Hybrid SMC parameters (Kp and Ki) and improve the performance of the system.

The third work proposed to tune the hybrid SMC parameters using a meta-heuristic algorithm for the system under various faults conditions such as Three Phase fault, Line to Ground fault(L-G), Line to Line (L-L) fault, Double Line to Ground (LLG) faults [15].

5. Contributions

5.1. Development of Hybrid Sliding Mode Controllers based PI controller for STATCOM

The proposed block diagram for the research work is shown in Figure 1. Here various STATCOM controllers are proposed to generate PWM pulses for the STATCOM controllers under various load conditions such as inductive loads, unbalanced loads and nonlinear loads. The various components in the proposed block diagram is STATCOM, STATCOM controllers and LCL filter.

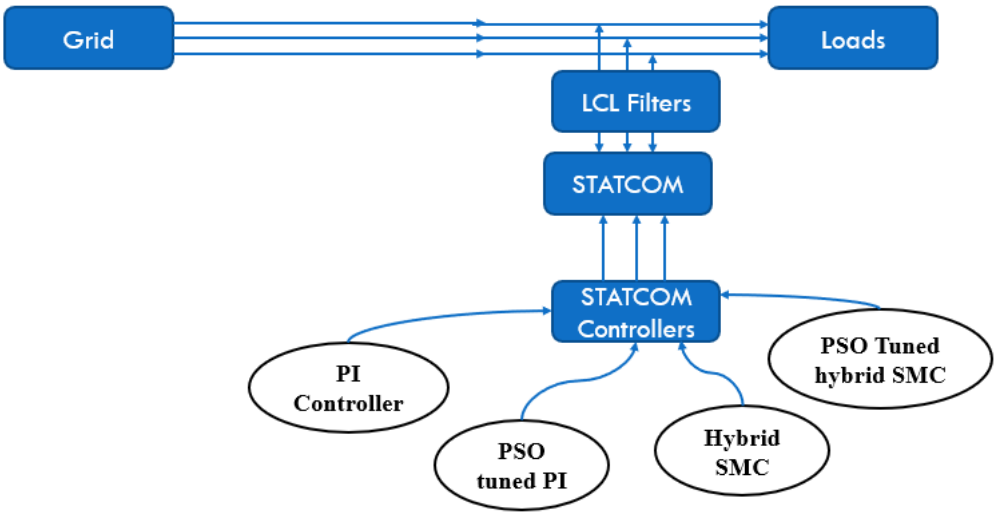

Figure 1: Block diagram

The Sliding mode controllers offer robust control strategy for managing nonlinear and uncertain systems. Their ability to drive system states to a desired sliding surface and maintain them there despite uncertainties makes them highly valuable in many critical applications. The basic architecture of the SMC is depicted in Figure 2.

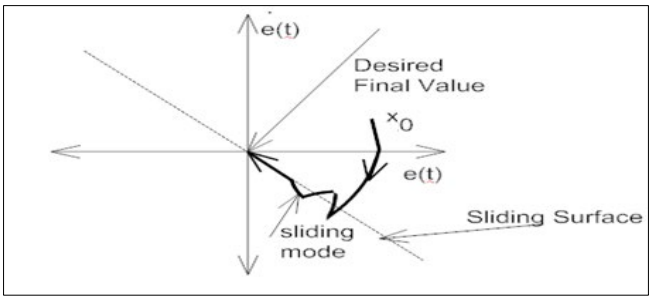

Figure 2: SMC controller's Graphical representation

The Hybrid Sliding Mode Controllers (HSMCs) are advanced control systems that combine the principles of traditional sliding mode control with other control techniques to enhance performance, reduce chattering, and improve robustness. In the proposed work the sliding surface is designed with proportional plus integral actions with e(t). The proposed controller output has a continuous part and the discrete part. So, the SMC is called as a hybrid SMC. S(t) is defined as,

$$S(t) = kpe(t) + Ki \int e(t)dt$$

Where e(t) is the error between the reference trajectory and d or q component of voltage. Kp and Ki are the gain parameters of the hybrid SMC.

The higher-order LCL filter is used for smoothing the output currents from the VSI. The current injected into the grid depends on the values of the inductance and capacitance of the LCL filters. So, with the low values of inductance and capacitance, the best performance can be obtained. While designing the LCL filter, it is necessary to make sure the stability of the filter at low-frequency and switching frequency conditions. The design parameters of the LCL filter for the proposed system is emphasized in Table 1.

Table 1: Design values for LCL filter

Switching frequency (Fsw)	10 KHz
Resonant frequency	1000Hz
C	100μF
L	500μH
Base Power	100KVA
Grid Voltage	415 V Ph-Ph, 50Hz

The SPWM control method is employed for producing the necessary gating pulses for the IGBT switches. The constant switching frequency capability of the SPWM decreases the stress levels on the converter switches. Hence irrespective of the load change, the voltage at PCC (V) is maintained. The block diagram of the proposed control scheme is illustrated in Figure 3. Synchronous Reference Frame Theory is chosen for generating the reference current. DC voltage, Load current (i_a, i_b and i_c) and Voltage at PCC (v_a,v_b and v_c) are sensed and given to the controller as feedback signals.

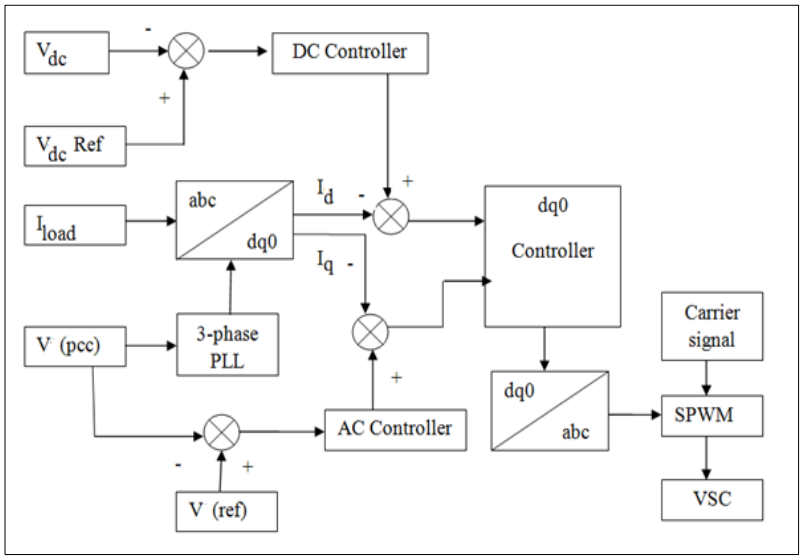

Figure 3: Control method for proposed STATCOM

Table 2: STATCOM with Hybrid SMC for inductive load

Case	Before Compensations					After Compensations				
	Load Side		Grid Side			STATCOM		Grid Side		
	P (kW)	Q (kVAr)	P (kW)	Q (kVAr)	Power factor	P (kW)	Q (kVAr)	P(kW)	Q (kVAr)	Power factor
1	11.7	24.5	11.7	24.5	0.431	0.07	21.14	12	-0.3	0.988
2	11.7	14.8	11.7	14.8	0.62	-0.5	11.99	11.88	-0.259	0.988
3	11.7	10.9	11.7	10.9	0.732	-0.11	9.691	11.77	-0.2438	0.989

The proposed system is simulated using MATLAB/Simulink, the various loads are tested in the system. The proposed system controllers effectively worked during abnormal conditions such as uncertain load variations, nonlinear loads and etc., Based on the information presented in that Table 2, it is evident that the reactive power of the grid is higher when STATCOM is not there, but the power factor is lower. Through the process of shunting the Hybrid SMC-based STATCOM with load, the reactive power is compensated by the STATCOM, which ultimately results in an improvement in the power factor of the grid.

The following Figure 4 represents the Voltage and current waveform of the Grid and Load for inductive load with Hybrid SMC based STATCOM. From these figures, it is inferred that the lagging current in the load is compensated in the Grid by the Hybrid SMC based STATCOM.

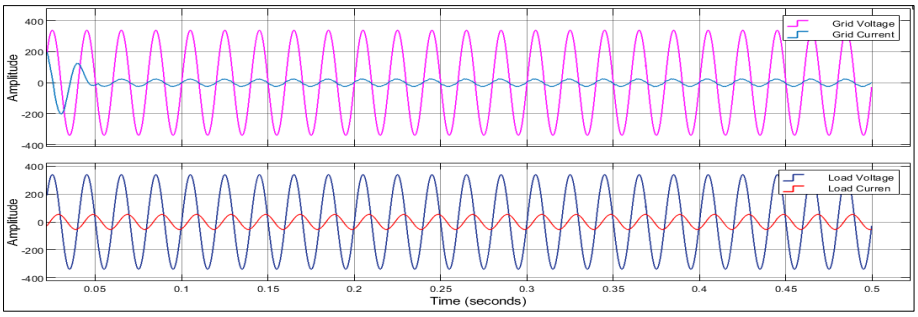

Figure 4 : Voltage and current waveform of the Grid and Load for inductive load with Hybrid SMC based STATCOM

The following Table 3 shows the load and grid parameters before and after reactive power compensation for the unbalanced load. From the table, it is inferred that reactive power is well compensated by the Hybrid SMC based STATCOM and the power factor is enhanced from 0.6853 to 0.9812.

Table 3 : STATCOM with Hybrid SMC for unbalanced load

Before Compensations					**After Compensations**				
Load Side		Grid Side			STATCOM Side		Grid Side		
P (kW)	Q (kVAr)	P (kW)	Q (kVAr)	Power factor	P (kW)	Q (kVAr)	P (kW)	Q (kVAr)	Power factor
18.1	19.2	18.06	19.2	0.6853	-1.508	17.06	19.93	-3.717	0.9812

The unbalanced load was connected from 0.2 to 0.4sec. From the figure, it is inferred that the sudden disturbance was handled by the Hybrid SMC smoothly but still the initial overshoot is more which is shown in Figure 5.

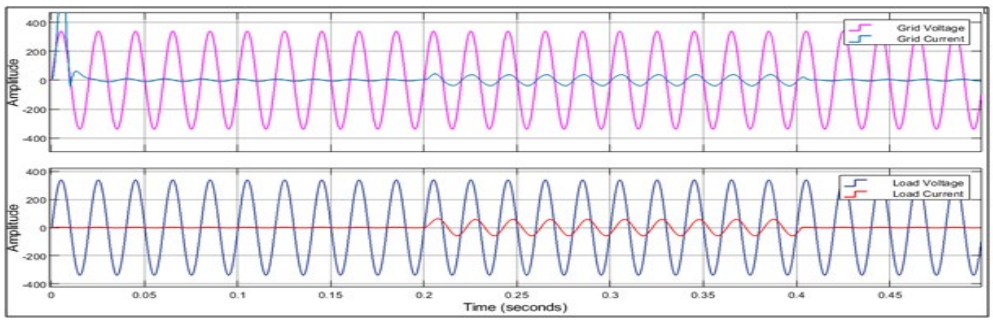

Figure 5: Voltage and current waveform of the Grid and Load for unbalanced load with Hybrid SMC based STATCOM

The following Table 4 shows the grid and load parameters before and after reactive power compensation to examine the performance of the hybrid SMC based STATCOM for a nonlinear load. From the table, it is inferred that the Hybrid SMC-based STACOM improved the power factor from 0.8166 to 0.9294.

Table 4: STATCOM with Hybrid SMC for Nonlinear load

Before Compensations					**After Compensations**				
Load Side		Grid Side			STATCOM Side		Grid Side		
P (kW)	Q (kVAr)	P (kW)	Q (kVAr)	Power factor	P (kW)	Q (kVAr)	P (kW)	Q (kVAr)	Power factor
7.099	5.018	7.099	5.118	0.8166	-0.101	4.169	7.226	1.585	0.9294

Figure 6 depicts the voltage and current waveforms of the grid with Hybrid SMC-based STATCOM for a non-linear load. Despite the fact that the current is sinusoidal, it has an inconsistent shape till 0.22 sec from 0.4 sec.

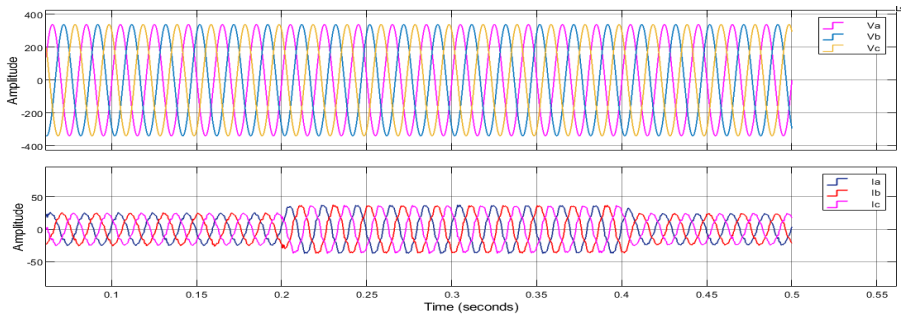

Figure 6: Voltage and current waveform of the Grid and Load for Nonlinear load with Hybrid SMC based STATCOM

When compare with conventional PI controllers the performance of the Hybrid SMC-based STATCOM were better. But still, the initial overshoot is more and the initial settling time is 0.05sec which is higher.

5.2 Apply a meta-heuristic algorithm to tune Hybrid SMC parameters to get optimal solution for various load conditions.

In previous work, proposed hybrid SMC, Kp and Ki are the two adjustable parameters to keep the controller output at the sliding surface to eliminate the errors. So it is essential to decide the optimum values for Kp and Ki. The performance metric of the controllers is an Integral Squared Error (ISE), Integral Absolute Error (IAE). So Controllers designed with minimizing ISE results in the fast elimination of larger errors, but small errors that continue for a long period of time will be tolerated.

$$f(x) = min(ISE)$$

For this minimization, it is essential to choose appropriate optimization algorithms. PSO is more suitable for tuning the controller parameters as per the discussion in literature survey. PSO-tuned controller offers a better dynamic response with minimum overshoot, less oscillations and less transient period and it does not show minute ripples in the steady state. During each iteration of the algorithm, each solution is evaluated by an objective function to determine its fitness. At the end of all iterations, the effectiveness of every particle is evaluated in terms of their proximity to the objective function by replacing the values of the vector elements in the objective function. PSO parameters for the Hybrid SMC to optimize the Kp and Ki values are given in Table 5. The optimum values for the Hybrid SMC controllers were, Kp_1=1.3218 Ki_1=1.1509 Kp_2= 2.2989 Ki_2=2.3876 Kp_3= 0.5687 Ki_3=1.4744 Kp_4=1.3423 Ki_4=1.9425.

Table 5: Parameters for proposed PSO tuned hybrid SMC

No of Variables	8
Maximum number of iterations	80
PSO Parameters	C_1=2; C_2=2
	Inertia weight w_{max} = 0.9 and w_{min} = 0.2
PI Parameters	0.01<Kp<8; 0.01<Ki<8

The proposed simulation work is depicted in Figure 7. The simulation was done by the LCL proposed values from Table 1 along with the DC side capacitor value is 5600µF and V_{dc} is 800V.

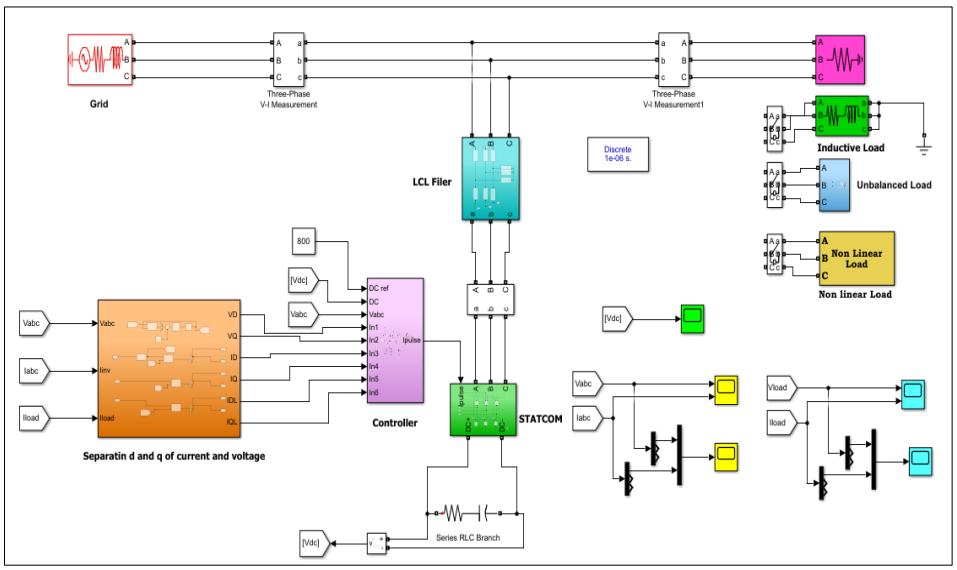

Figure 7: The overall circuit simulation of the proposed controller

The following Figure 8 shows that the block diagram for PSO tuned hybrid SMC based STATCOM. In the simulation diagram, LCL filters, STATCOM and its controllers, Different load conditions are indicated.

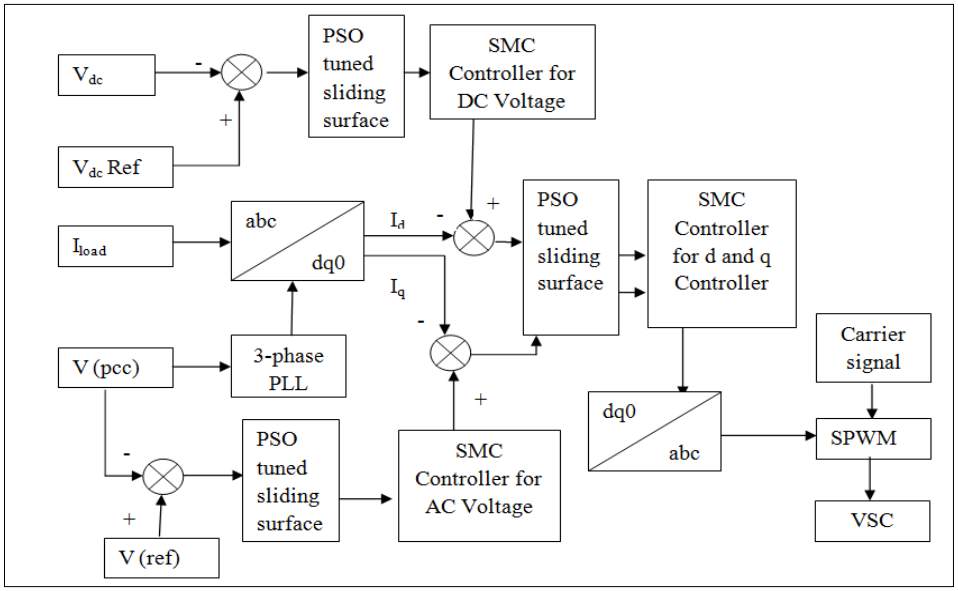

Figure 8: block diagram for PSO tuned hybrid SMC based STATCOM

The following Figure 9 shows that DC capacitor voltage. it is clear that the DC voltage peak amplitude is reduced and settled at 0.002sec

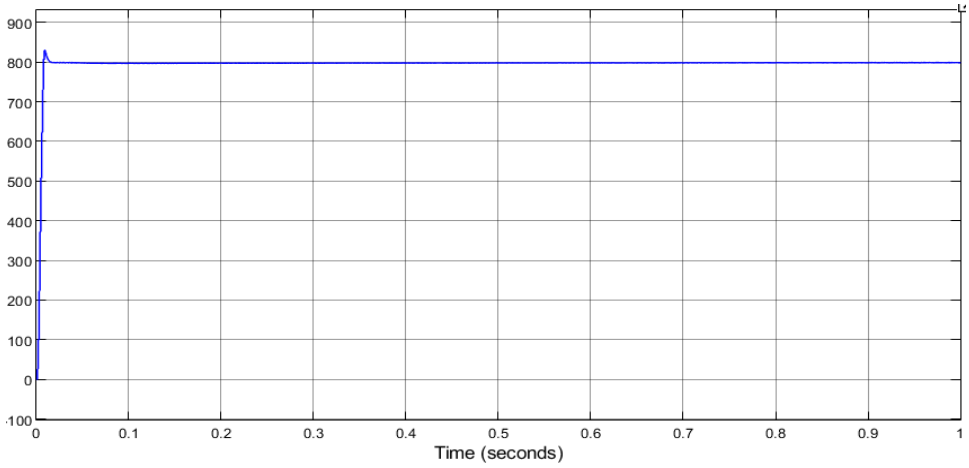

Figure 9: DC voltage across the Capacitor

In the proposed STATCOM with PSO tuned hybrid SMC is tested under various load conditions as per previous works. The load and grid side values before and after compensations are given in the following Tables 6,7 and 8.

Table 6: STATCOM with PSO tuned Hybrid SMC for inductive load

Case	Before Compensations					After Compensations				
	Load Side		Grid Side			STATCOM Side		Grid Side		
	P (kW)	Q (kVAr)	P (kW)	Q (kVAr)	Power factor	P (kW)	Q (kVAr)	P(kW)	Q (kVAr)	Power factor
1	11.7	24.5	11.7	24.5	0.431	-0.13	24.477	11.72	-1.192	0.995
2	11.7	14.8	11.7	14.8	0.62	-0.11	14.7	11.7	0.389	0.992
3	11.7	10.9	11.7	10.9	0.732	-0.18	10.6	11.7	0.284	0.995

Table 7: STATCOM with PSO tuned Hybrid SMC for unbalanced load

Before Compensations					After Compensations				
Load Side		Grid Side			STATCOM Side		Grid Side		
P (kW)	Q (kVAr)	P (kW)	Q (kVAr)	Power factor	P (kW)	Q (kVAr)	P (kW)	Q (kVAr)	Power factor
18.07	19.2	18.06	19.2	0.6853	-1.98	18.45	19.93	2.58	0.9917

Table 8: STATCOM with PSO tuned Hybrid SMC for Nonlinear load

Before Compensations					After Compensations				
Load Side		Grid Side			STATCOM Side		Grid Side		
P (kW)	Q (kVAr)	P (kW)	Q (kVAr)	Power factor	P (kW)	Q (kVAr)	P (kW)	Q (kVAr)	Power factor
7.099	5.018	7.099	5.118	0.8166	0.205	4.958	7.108	0.158	0.9817

The step response parameters such as overshoot undershoot, settling time and rise time of PSO tuned PI controller, Hybrid SMC and PSO tuned Hybrid SMC were measured and compared. The following Table 9 shows that comparison between proposed and conventional controllers.

Table 9 : Comparison of controllers parameters

Controller/ Parameter	PSO tuned PI controller	Hybrid SMC	PSO tuned Hybrid SMC
Overshoot (%)	13.068	10.556	2.604
Undershoot (%)	1.989	1.975	1.095
Settling time(ms)	11.082	10.345	5.621
Rise Time(ms)	4.577	7.031	5.099

From Table 9 inferred that the PSO tuned PI controller has the highest overshoot 13.068% and the PSO tuned Hybrid SMC has the lowest overshoot 2.60%. The PSO

tuned Hybrid SMC has a minimum overshoot of 1.095% and minimum settling time of 5.621ms compared with PI tuned PSO and Hybrid SMC. So, according to this table, it is inferred that the PSO tuned Hybrid SMC provides the best performance compared with PI tuned PSO and Hybrid SMC.

The following Figure 10 shows a bar chart of improvement in power factor with and without STATCOM for inductive load, unbalanced load and nonlinear load. PSO tuned Hybrid controller-based STATCOM improved the power factor of the inductive load, unbalanced load as well as the nonlinear load when compare with hybrid SMC based STATCOM.

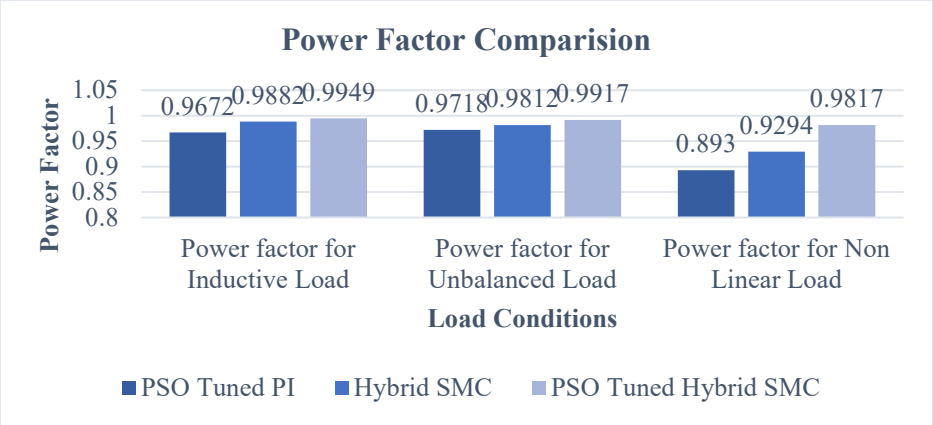

Figure 10: Power factor comparison for conventional and proposed controllers

Table 10: THD Values of Grid current with LC and LCL filters for nonlinear load

Load Type	Phase	Grid Current THD in %						
		Without STATCOM	With PSO tuned PI-based STATCOM		With Hybrid SMC based STATCOM		With PSO tuned Hybrid SMC based STATCOM	
			LC Filter	LCL Filter	LC Filter	LCL Filter	LC Filter	LCL Filter
Nonlinear Load	A	16.72	14.12	8.8	13.25	5.76	12.53	2.24
	B	14.93	14.28	9.21	13.75	5.06	12.63	2.37
	C	16.3	14.93	9.218	13.86	5.45	12.86	2.35

The performance of the proposed PSO tuned Hybrid SMC based STATCOM was examined with LC and LCL filters for a nonlinear load since the non-sinusoidal load current waveform caused more harmonics. So, it is necessary to mitigate the harmonics as much as possible to improve the performance of the grid. The following Table10 compares grid current THD with LC and LCL filters for nonlinear loads using

proposed controllers. From that table 10 inferred that LCL filter with PSO tuned Hybrid SMC based STACOM reduce the THD values from 16.72% to 2.24% in Phase A, 14.93% to 2.37% in phase B and 16.30% to 2.35% in phase C. Compared with the PSO tuned PI and Hybrid SMC, the PSO tuned Hybrid SMC based grid current waveforms are smoothen sinusoidal which gives less THD value.

Figure 11 shows the harmonic spectrum of the grid current of the proposed controller with LCL filter. From this, it is inferred that the highest fundamental harmonic value is 26.04 and the THD value is 2.35%.

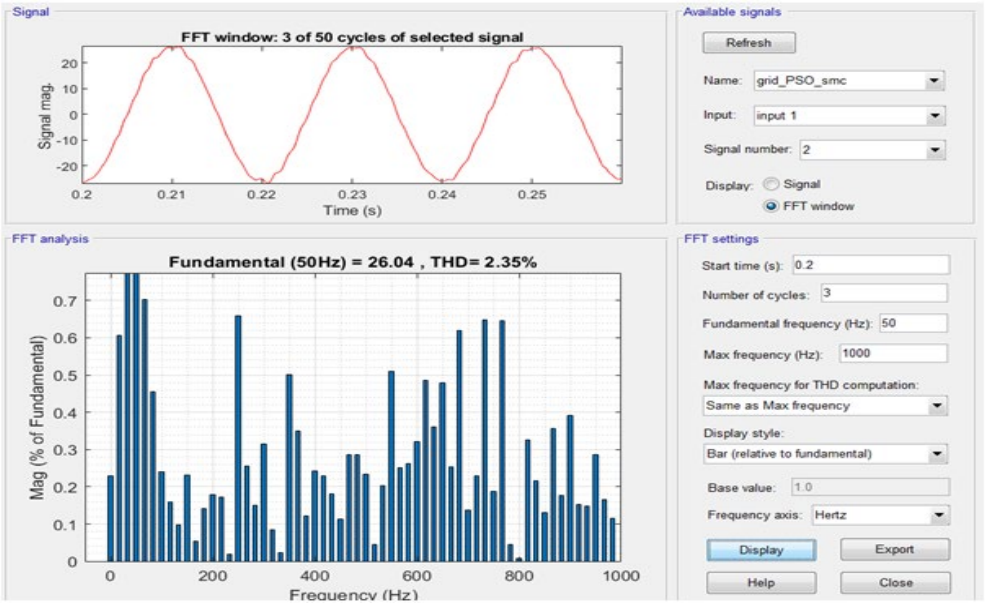

Figure 11 : Harmonic spectrum Grid current for STATCOM with LCL Filter

In this proposed scheme, the PSO optimized hybrid SMC with STATCOM was simulated with an inductive load, unbalanced load and Non-linear load. From the simulation, it is studied that the reactive power consumed by the inductive load was successfully compensated by the proposed controller and the power factor of the Grid was also improved. The proposed controller handles the sudden load changes smoothly and improves the performance.

5.3 Apply the meta-heuristic algorithm to tune the STATCOM parameters under various Fault conditions.

In this proposed work investigate the PSO-tuned hybrid SMC performance based VSC-STATCOM under different conditions of fault using hybrid renewable energy sources (HRES). A hybrid renewable energy resource system (HRES) consists of PV, wind power, and batteries. Here the Irradiance is the PV input and the wind energy is Wind Input. The storage of energy is used for battery. The HRES systems

may not supply adequate reactive power during system faults, leading to fluctuating voltage profiles at common connection points and adverse effects on power streams. Issues such as voltage sag and swell, power factor, and PQ (Performance and Quality) parameters can have undesirable consequences if not appropriately managed, in accordance with relevant grid codes. The proposed work controller is applied to the system under various fault conditions such as three phase faults, Line to Line fault, Line to ground fault(L-G) and Double Line to Ground faults (LLG).

From the Figures 12,13 and 14 shows that a three-phase fault occurred at 0.08 seconds, resulting in a voltage dip across all three phases. The voltage dipped to 310 volts (30% sag) when utilizing PSO-PI of STATCOM, 390 volts (10% sag) with SMC, and 413 volts (3% sag) with PSO-SMC based STATCOM. At 0.08 seconds, the VSC-STATCOM became active and injected 101 volts for PSO-PI of STATCOM, 22 volts for SMC, and 2 volts for PSO tuned SMC.

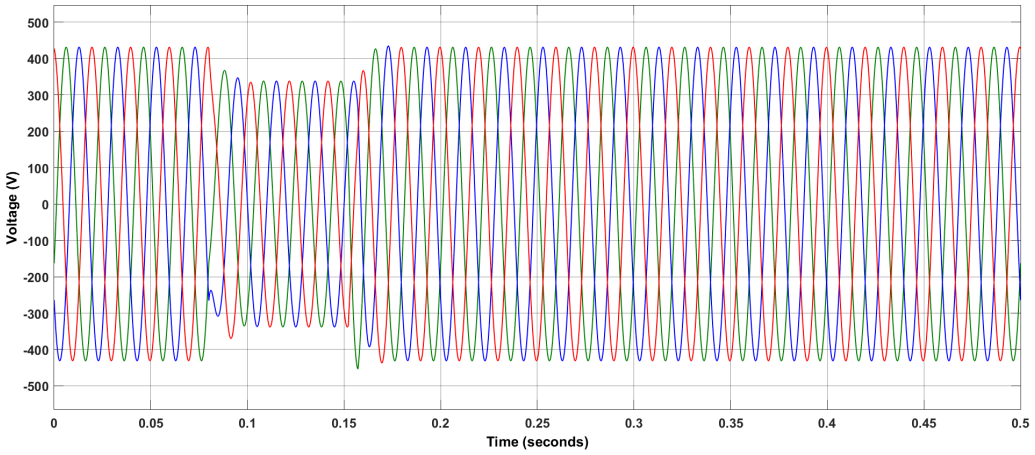

Figure 12 : Three phase fault voltage sag compensation of using PSO - PI

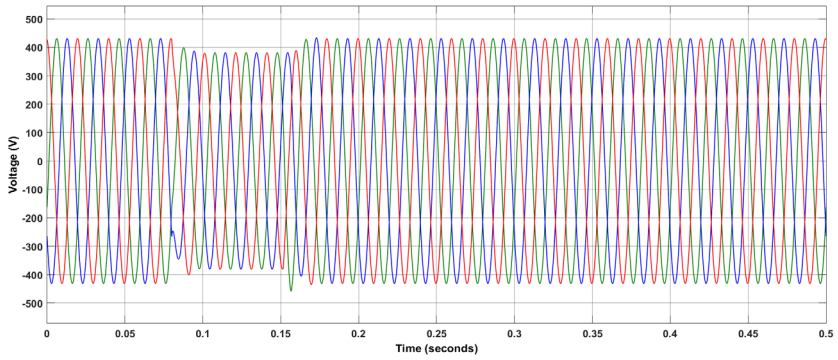

Figure 13 : Three phase fault voltage sag compensation of using Sliding Mode Controller

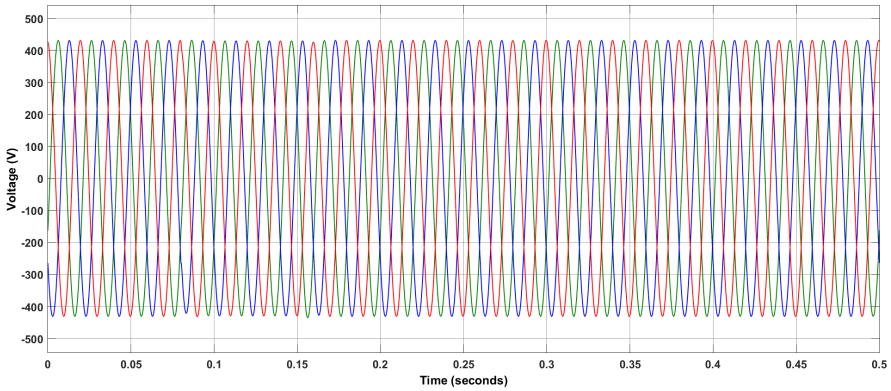

Figure 14: Three phase fault voltage sag compensation of using PSO tuned SMC based STATCOM

The proposed controllers applied to the three phase faults (as shown in above figures), Line-to-Line fault (L-L), Single Line to Ground Fault (L-G) and Double Line to Ground Fault Compensation (L-L-G) are simulated and injected voltage and current values are listed in Table 11 and 12.

Table 11. The proposed and existing techniques compensated voltage comparison

Optimization techniques	Three phase fault		Line to line fault				Single line to		Double Line to ground fault			
	Voltage (V)	Injected Voltage (V)	Phase A	Injected Voltage (V)	Phase B	Injected Voltage (V)	Phase A	Injected Voltage (V)	Phase A	Injected Voltage (V)	Phase B	Injected Voltage (V)
PSO tuned PI	310	101	320	80	330	70	280	130	315	80	320	70
SMC	390	22	395	18	405	9	395	18	390	18	395	9
PSO-SMC	413	2	412	3	413	2	405	10	413	3	413	2

Table 12. The proposed and existing techniques compensated current comparison

Optimization techniques	Three phase fault		Line to line fault				Single line to ground fault		Double Line to ground fault			
	Current (A)	Injected Current (A)	Phase A	Injected Current (A)	Phase B	Injected Current (A)	Phase A	Injected Current (A)	Phase A	Injected Current (A)	Phase B	Injected Current (A)
PSO tuned PI	11	11	16	9	18	7	14	10	16	7	17	9
SMC	18	9	19	5	21	4	19	5	20	5	21	5
PSO-SMC	22	3	22	3	24	1	22	3	23	2	24	1

From above Tables 11 and 12, the proposed PSO tuned hybrid SMC controllers is effectively worked well and it is superior than other convention controllers for various fault conditions. With help of the proposed controllers, system remains good during abnormal fault conditions.

6. Conclusions

The STATCOM operated effectively with proposed controller such as hybrid SMC, PSO tuned hybrid SMC to enhance power quality. The system is tested with various kinds of loads such as Nonlinear, unbalanced and inductive loads. The proposed controllers worked efficiently to reduce supply of reactive power from source and reduce harmonics in power system. The proposed LCL filter with PSO tuned Hybrid SMC based STACOM reduce the grid current THD values from 16.72% to 2.24% in phase A and other phase THD values also nearer to it. It reflects that system parameters are within ranges described by IEEE and IEC. Any load changes that occurred were taken into account when tuning the controller's parameters to keep them within acceptable ranges. The HRES system is tested under three-phase fault compensation, Line-to-Line fault compensation, and Single Line to Ground Fault Compensation, along with Double Line to Ground Fault Compensation. The STATCOM functions to adjust voltage levels during various fault conditions. Multiple control methodologies are examined to improve the efficacy of the proposed STATCOM. The particle swarm optimization-based hybrid sliding mode controller has exceptional efficiency in real and reactive power compensation among these approaches.

In the future, this system may incorporate additional optimizations and sophisticated controllers to accommodate a variety of load conditions, including the Interactive Decision Tree-based Fuzzy-PID Controller and Biography-Based Optimization. In the future, the proposed system may be tested using further FACTS devices, such as DVR and UPQC. The prototype may be implemented in the future for evaluating the simulated results.

7. Organization of thesis

The organization of the proposed thesis work is clearly described as below, the introduction about power, a summary of power quality and its many problems, PQ standards, FACTS devices, and the significance of STATCOM are all covered in Chapter 1. The literature review of STATCOM and the various controllers used to improve PQ were covered in detail in Chapter 2. The STATCOM, LCL filter design methodology and parameters calculations are covered in chapter 3. Designing hybrid SMC-based PI controllers for STATCOM was covered in Chapter 4. MATLAB/Simulink is used to run the simulation and results are validated with various load conditions such as inductive, unbalanced and nonlinear loads. The use of a PSO-

tuned hybrid SMC controller in STATCOM was covered in Chapter 5. The findings demonstrate that, in the test system with varying loads, reactive power compensation and power factor improvement are accomplished. The proposed PSO tuned hybrid SMC power factor values are compared with conventional controllers in this chapter. The HRES systems simulation is tested under various fault conditions are covered in chapter 6 along with voltage and current injections during fault conditions are listed. The Conclusion and the scope for future research have been provided in Chapter 7 and reference as follows.

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List of Publications

1. Rajendran, S., A. Muthu Kumar, and V. Agnes Idhaya Selvi. Particle Swarm Optimization tuned Hybrid Sliding Mode Controller based static synchronous compensator with LCL filter for Power Quality improvement. Sustainable Energy Technologies and Assessments **53** (2022): 102653.
2. Rajendran, S., A. Muthukumar, K. Vijayakumar, and K. Rajesh. VSC-STATCOM Performance Under Different Fault Sensing using PSO Tuned Hybrid SMC *International Journal of Electrical and Electronics Research* **12** (2) (2024), 478-486.
3. Rajendran, S., A. Muthu Kumar, T. Arunprasath, M. Pallikonda Rajasekaran, Kottaimalai Ramaraj, and S. Kalimuthukumar. *Model Predictive Control Based STATCOM to Enhance Power Quality in Power System*. In 2023 International Conference on Self Sustainable Artificial Intelligence Systems (ICSSAS), 2023 1595-1598.